Proceedings of the Conference on

Recent Advances in Active Control of Sound and Vibration

General Chairman: C. R. Fuller
Technical Chairman: R. A. Burdisso
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Virginia Polytechnic Institute
and State University
Blacksburg, Virginia

15–17 April, 1991

Sponsored by:
NASA Langley Research Center
Office of Naval Research
U.S. Army Aerostructures Directorate

TECHNOMIC
PUBLISHING CO., INC.
LANCASTER • BASEL

Recent Advances in Active Control of Sound and Vibration
a TECHNOMIC publication

Published in the Western Hemisphere by
Technomic Publishing Company, Inc.
851 New Holland Avenue
Box 3535
Lancaster, Pennsylvania 17604 U.S.A.

Distributed in the Rest of the World by
Technomic Publishing AG

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

Main entry under title:
Recent Advances in Active Control of Sound and Vibration

A Technomic Publishing Company book
Bibliography: p.

Library of Congress Card No. 91-65229
ISBN No. 87762-839-4

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ELECTROMECHANICAL MODELLING OF AN ACTIVE ISOLATION SYSTEM

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ABSTRACT

The importance of detailed modelling of control element dynamics is demonstrated for the case of a distributed piezoelectric vibration isolator composed of a piezocomposite actuator/sensor combination mounted on a uniformly vibrating surface in air. Several system transfer functions were obtained during preliminary measurements, including the ratio of the acceleration of the top surface of the composite structure to the voltage out of the sensor element. It was discovered that this transfer function is different for the case of driving the base structure while leaving the actuator element open circuit, than for the case of driving the actuator while keeping the base rigid. The significance of this difference is that in the actual control situation, both the base structure and the actuator are driven; therefore, minimization of the sensor output does not necessarily imply minimization of the surface motion. The cause of and solution for this behavior is investigated using first a simple analytical model, and then a detailed finite element model. Results obtained using these models are compared with those obtained from experimental measurements.

INTRODUCTION

An accurate predictive model is an important tool for the designer of an active control system. Such a model can be used to determine optimum placement of actuators or to evaluate candidate materials without building and testing many different prototype systems. The amount of effort required to develop an adequate system model depends on both the nature of the control elements and the applicability of certain simplifying assumptions in the frequency range of interest. This paper will focus on the analysis of distributed piezoelectric actuators and sensors at frequencies below the first resonance of the composite isolator structure.

The usefulness of piezoelectric distributed sensors and actuators for active control/isolation applications has been demonstrated by a number of investigators. A variety of piezoelectric materials have been used, including various lead zirconate titanate (PZT) ceramics and piezoelectric polymers. Piezoceramics typically have higher electromechanical coupling coefficients than do piezopolymers, while the polymers are more rugged and offer the capability of bonding to curved surfaces.

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Bailey and Hubbard [1] used a piezoelectric polymer known as polyvinylidene flouride (PVDF) bonded to one complete surface of a cantilever beam as an active vibration damper. The system is modelled as a two-layer Euler-Bernoulli beam. A voltage applied through the thickness of the PVDF results in a transverse strain in both layers, through the effect of the d_{33} piezoelectric constant. The net force produced in each layer acts as a moment about the neutral axis of the composite beam. The thickness strain in the PVDF layer resulting from the d_{33} constant has a negligible influence on the motion of the base beam because of the small inertia developed in the low density polymer.

Further work with piezoelectric actuators was performed by Crawley and deLuis [2] who used pieces of piezoceramic bonded symmetrically to both sides of a cantilever beam to excite flexure in the beam by driving the actuators out of phase. It was shown that for a one-dimensional beam, the transverse strain produced in the actuators can be modelled as a moment applied at the ends of the actuator. This work was extended by Dimitriadis, et al. [3] to two-dimensional "patches" of piezoceramic. This analysis shows that the transverse strains in the actuators result in moments applied around the perimeter of the actuator area. In both investigations, the influence of the d_{33} piezoelectric constant, and the resultant thickness strain, is neglected.

A rather different application of piezoelectric actuators was proposed by Tzou and Gadre [4]. They bonded Plexiglas plates to each side of a thin slab of PVDF, then added a heavy plate to the top, and finally mounted the composite structure on a shaker. The signal from an accelerometer placed on the top of the structure was filtered and applied across the thickness of the PVDF in order to null the vibration of the top surface. In the associated analytical work, the transverse strains developed in the piezopolymer are neglected because of the stiffness of the attached layers and the large ratio of area to thickness. The behavior of the piezoelectric layer is described by the coupling between the voltage applied through the thickness and the strain developed in the thickness dimension (the d_{33} constant). This one-dimensional model is shown to describe adequately the behavior of the system.

The objective of the work presented here is similar to that of Tzou and Gadre [4], that is, to create an effectively rigid surface over a vibrating base structure using active control techniques. The vibration isolation element is made up of an actuator, which is mounted on the vibrating surface, and a sensor, which is bonded to the top surface of the actuator. The material used for both elements is a piezoelectric composite comprising lead titanate particles in a neoprene matrix (tradename PZR [5]).

The sensor and actuator are each composed of two circular layers of PZR, poled in the thickness direction, which are electrically in parallel. Thin, stiff, elastic layers separate successive layers of piezoelectric material. A stiffening layer is also bonded to the top of the composite element. The voltage out of the sensor is a function of the area average of the thickness strain and the extensional strain in the sensor material. This voltage is filtered using an appropriate control algorithm, and then becomes an input to the actuator. The function of the control algorithm is to minimize the sensor voltage. A sketch of the control element configuration is shown in Figure 1 where V_s is the voltage out of the

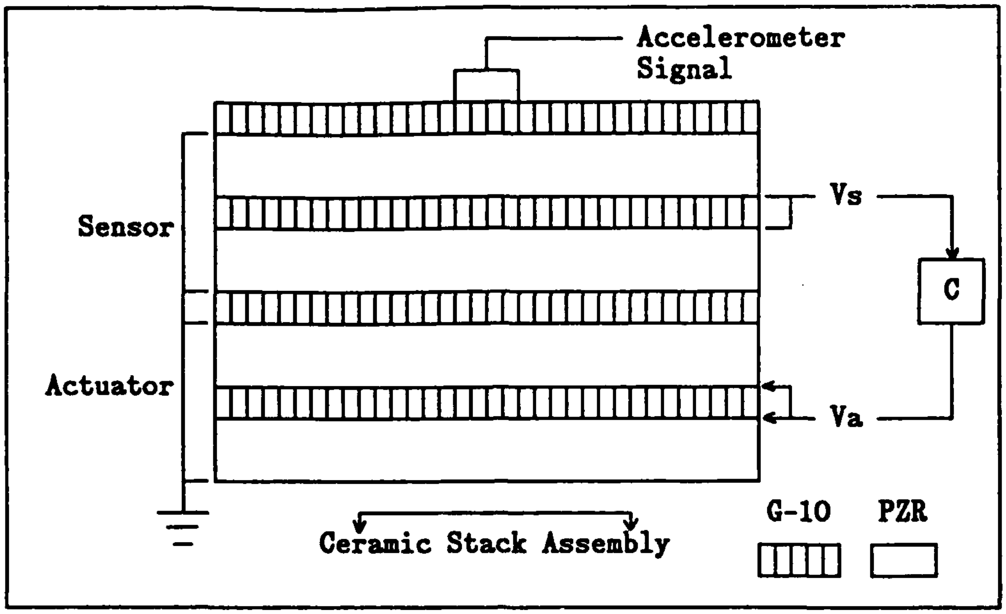


Figure 1. COMPOSITE ISOLATOR CONFIGURATION

sensor, V_a is the voltage into the actuator, and C is the controller. The development of the control algorithm is described in a companion paper [6].

Measurements of various transfer functions revealed that the ratio of the top surface acceleration, measured by an independent accelerometer, to the sensor output voltage is highly dependent on the drive conditions. This behavior was not predicted by a one-dimensional model of the isolator. Other possible explanations, including cross talk between the actuator and the sensor when driving the actuator, were eliminated. A more detailed model which includes extensional motion (through Poisson's ratio and the d_{31} constant) was developed using the finite element method. The transfer function predicted using this model demonstrated the same drive-dependent behavior as was found experimentally. In addition, the finite element method's capability of producing explicit graphical representations of the dynamic displacement field of the structure was useful in studying the behavior of the isolator structure.

ANALYSIS

In developing both the analytical and numerical models of the composite isolator, some basic assumptions are made about the nature of the materials. It is assumed that the elastic and piezoelectric properties of the materials are linear, lossless, and frequency independent over the frequency range of interest. In addition, the PZR layers are assumed to be perfectly bonded to the base plane and to the stiffening layers so that the effects of finite bonding layers are not considered.

The one-dimensional model of the composite isolator structure requires the further assumption that the effect of extensional motion of the piezoelectric layers on the thickness motion and on the sensor voltage is negligible. Also, the elastic stiffening layers are excluded from this model. The one-dimensional analysis is based on an equivalent circuit model of a single piezoelectric layer having only thickness motion [7] to

represent each of the isolator components. Two such circuits are cascaded to form the composite isolator model. The impedance terms (electrical Z_b, mechanical Z_s, and electromechanical Z_{em}) for each three-port network must be corrected to account for the fact that the actuator and sensor are each made up of two layers of PZR wired in parallel rather than a single layer of equivalent thickness. These corrections are as follows: $Z_b=Z_b'/4$, $Z_s=Z_s'$, and $Z_{em}=Z_{em}'/2$, where the prime indicates the impedance of a single layer of equivalent thickness. The system of equations is formed by writing an equation for each loop in the circuit in terms of the force at the base, the velocity of the actuator/sensor interface, the velocity of the top surface, the actuator current, and the sensor voltage. The base velocity and the actuator drive voltage are specified.

In developing the finite element model of the isolator, it is assumed that the vibration is axisymmetric so that it is necessary to model only a radial slice of the structure. This simplification reduces the number of degrees of freedom in the model from several hundred to about one hundred fifty, resulting in significantly shorter computational times. For a single isolator vibrating in air this is a reasonable assumption. The finite element code ATILA [8], which includes piezoelectricity, is used to develop the axisymmetric isolator model; the mesh is shown in Figure 2. The elements are eight-noded quadrilaterals based on a quadratic shape function. The boundary conditions are as follows: no displacements across the axis of symmetry, no extensional motion along the isolator/base interface, and uniform thickness displacement along the isolator/base interface. Results of the finite element and one-dimensional models will be presented later in the paper.

EXPERIMENTAL SET-UP

The actuator and sensor are each made up of two 0.125-inch-thick, 2.25-inch-diameter PZR discs which are poled in the thickness direction and electroded with thin copper foil and conductive adhesive (see Figure 1). The electroded PZR discs are separated by a 0.03-inch-thick disc of G-10 composite. The sensor is shielded from the actuator and the ceramic stack by copper foil. An accelerometer is mounted on the top surface of the isolator in order to provide an independent measurement of the surface to be controlled. An additional accelerometer is bonded to the base plate. The base is driven by a compliantly mounted piezoelectric ceramic stack having a fundamental resonance frequency near that of the isolator.

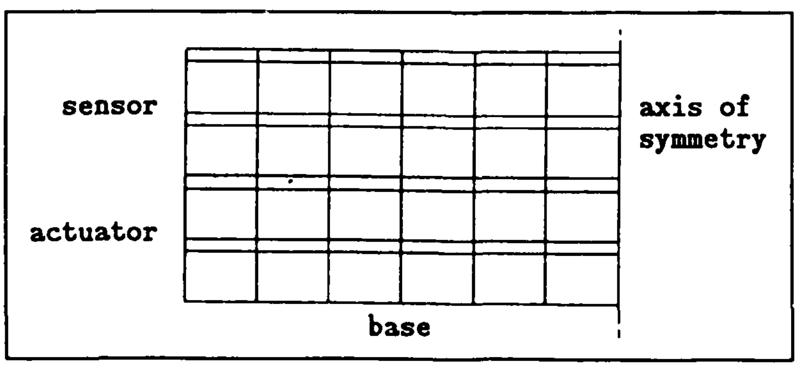


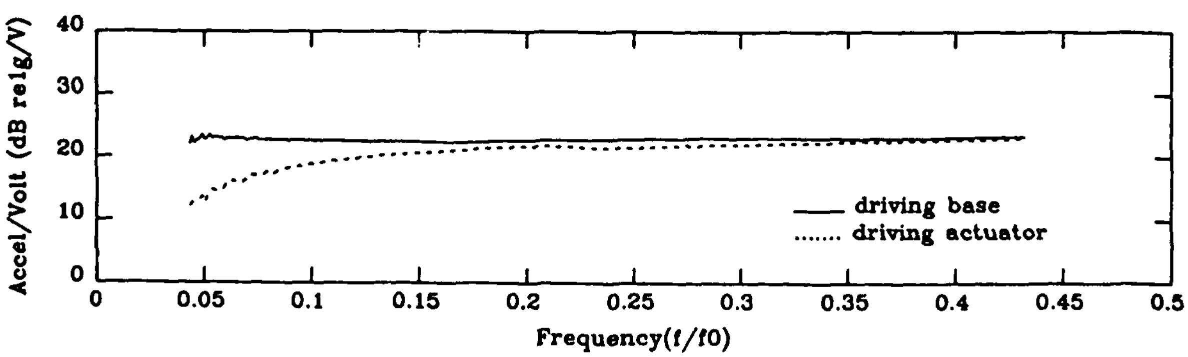
Figure 2. FINITE ELEMENT MESH

RESULTS AND DISCUSSION

Because of the frequency dependence of the ceramic stack compliance, measured accelerations and voltages depend on the response of not only the isolator but also the ceramic stack; therefore only ratios of measured quantities may be compared to model results. In this section, measurements of the acceleration to sensor voltage ratio are compared with results obtained from the one-dimensional and finite element models. Further model results for different boundary conditions and material properties are then presented in order to explain the cause of, as well as to determine a solution to, the problem of the drive-dependent transfer function.

In Figures 3(a), (b), and (c), the transfer function between the sensor voltage and the surface acceleration (obtained from measured data, the finite element model, and the one-dimensional model, respectively) is presented. The measured data demonstrates that this ratio is nearly constant with frequency when the base is excited; but when the actuator is driven, the ratio is approximately 10 dB down at the lowest frequencies and increases with frequency until the levels match those of the base-driven case. The transfer function obtained from the one-dimensional model is independent of drive conditions, indicating that the assumption of no extensional motion is not valid. Conversely, the results of the finite element model demonstrate the same drive dependence of the transfer function as was found experimentally. A comparison of Figures 3(a) and (b) shows that the model predicts approximately the same difference between the transfer functions as the measured results, although the absolute levels of the predicted results are between 1 and 3 dB lower than measured levels. This difference between predicted and measured levels is attributable to inaccurate material constants and the actual frequency dependence of the material properties in addition to experimental error.

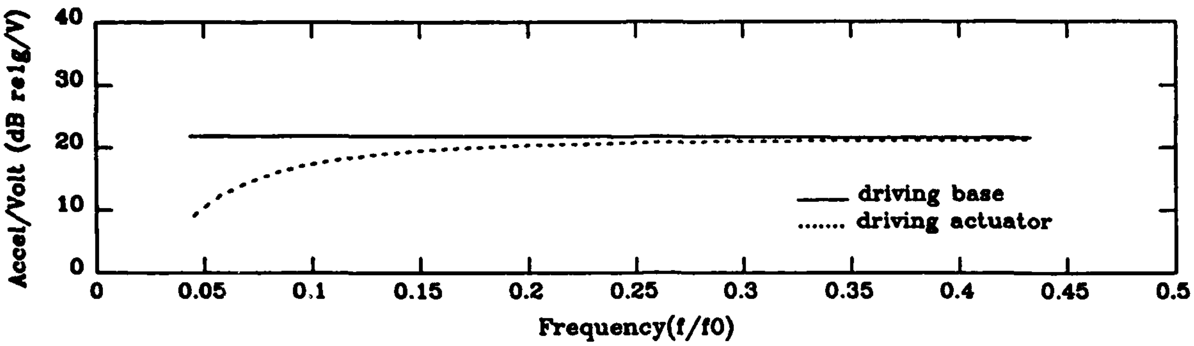
In Figures 4 and 5, the harmonic displacement fields for the lowest ($0.05f_0$) and highest ($0.45f_0$) frequencies are shown for the two drive cases. Figures 4(a) and (b) demonstrate that the voltage applied across the actuator results in significant extensional displacement in the actuator, through the d_{31} piezoelectric coupling, and in the sensor, through the mechanical coupling of the two elements, at both the low and



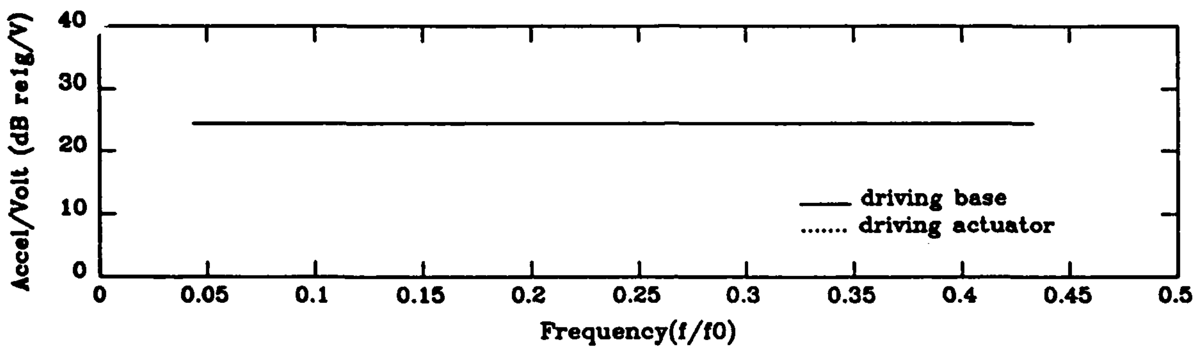
3(a) Measured Data (continued)

Figure 3. RATIO OF SURFACE ACCELERATION TO SENSOR VOLTAGE

(Figure 3. continues)



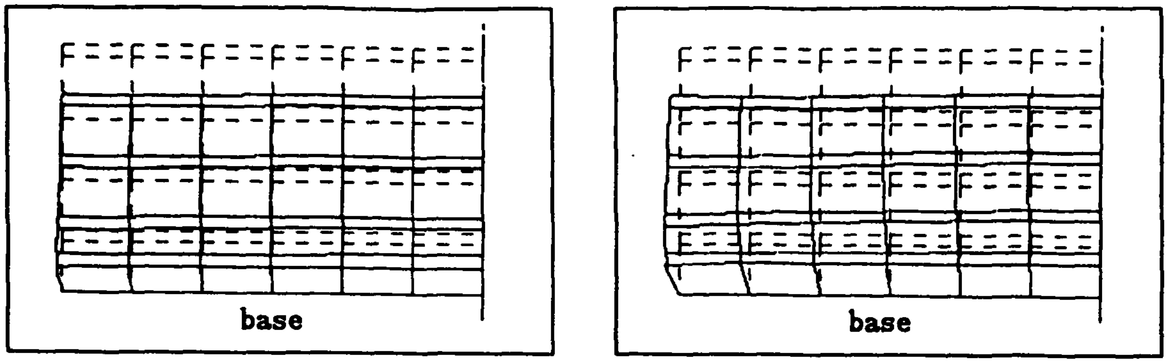
3(b) Finite Element Model



3(c) One-dimensional Model

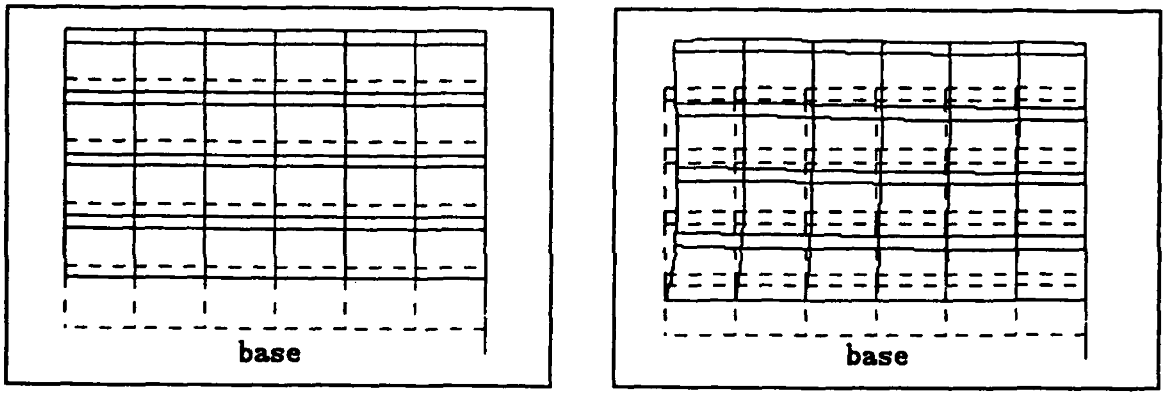
high frequencies. Conversely, it is seen in Figure 5(a) that for the case of driving the base at low frequencies, the isolator moves as a rigid body with no extensional motion. At the high frequency, however, the base-driven structure demonstrates the Poisson effect and the displacement field becomes similar to that of the actuator-driven structure as shown in Figure 5(b). At frequencies for which the normalized displacement fields are similar for the two drive cases, the corresponding transfer function levels agree.

Results of the finite element and one-dimensional models are compared in Figures 6(a) and (b) for the surface acceleration and the sensor voltage, respectively, for the case of driving the actuator. The corresponding results for the case of driving the base are shown in Figures 7(a) and (b). These figures show that there is little difference between the surface accelerations predicted by the two models; however, there is a large difference between the results for the sensor voltage. The voltage predicted by the one-dimensional model is lower than that predicted by the finite element for both drive conditions. This is not surprising since the sensor voltage is a result of both the d_{33} and the d_{31} coupling of strain to electrical potential.



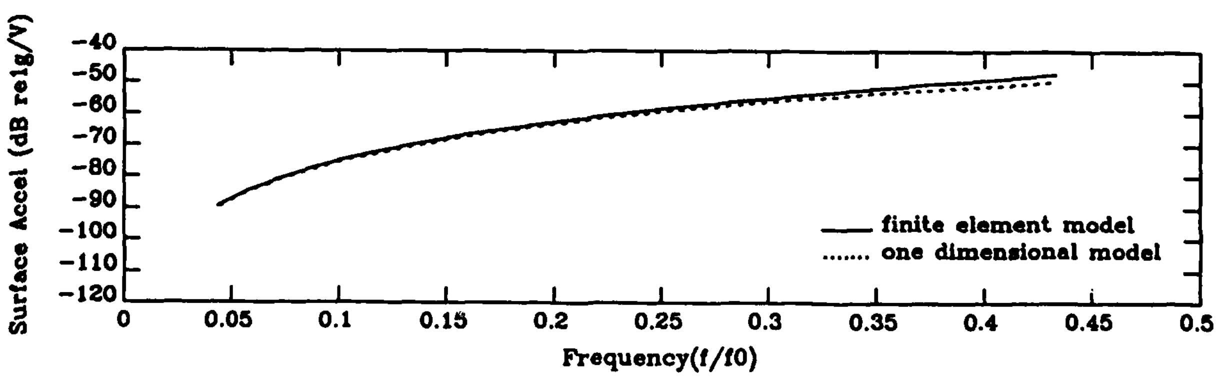
4(a) Frequency = $0.05f_0$ 4(b) Frequency = $0.45f_0$

Figure 4. NORMALIZED DISPLACEMENT FIELD FOR ACTUATOR-DRIVEN CASE (___deformed, ---undeformed)



5(a) Frequency = $0.05f_0$ 5(b) Frequency = $0.45f_0$

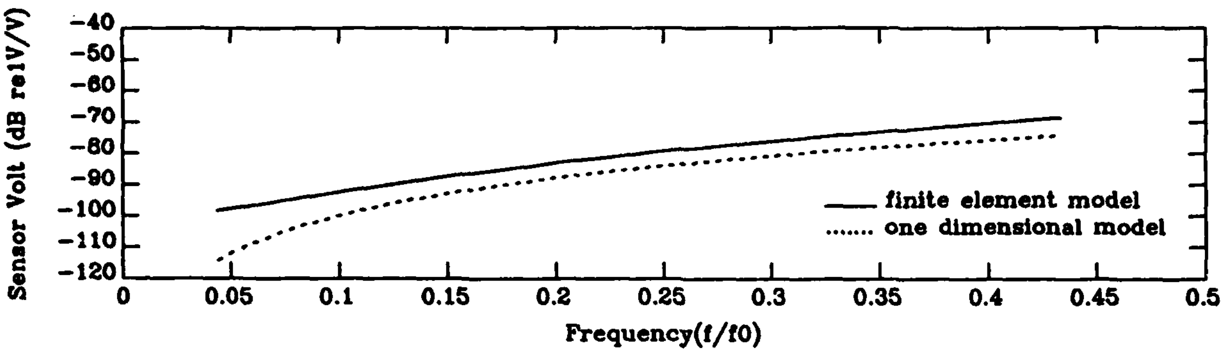
Figure 5. NORMALIZED DISPLACEMENT FIELD FOR BASE-DRIVEN CASE (___deformed, ---undeformed)



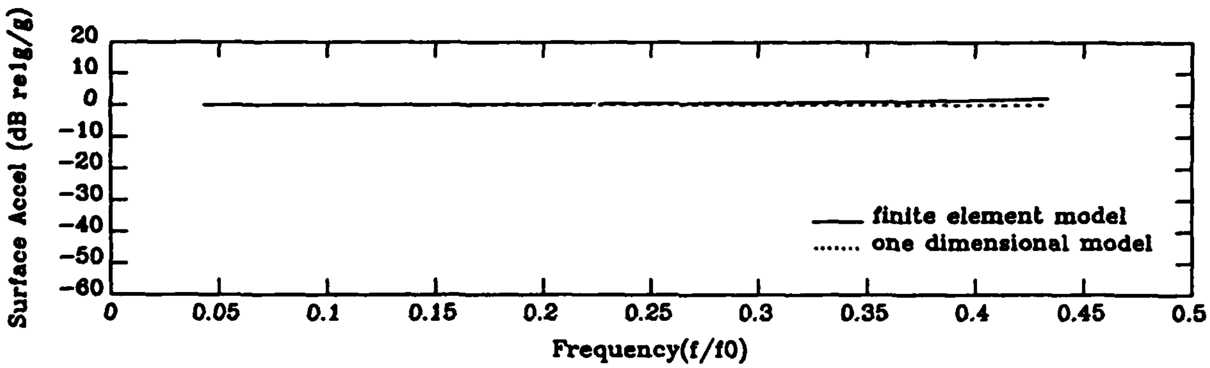
6(a) Surface Acceleration (continued)

Figure 6. MODEL RESULTS FOR ACTUATOR-DRIVEN CASE

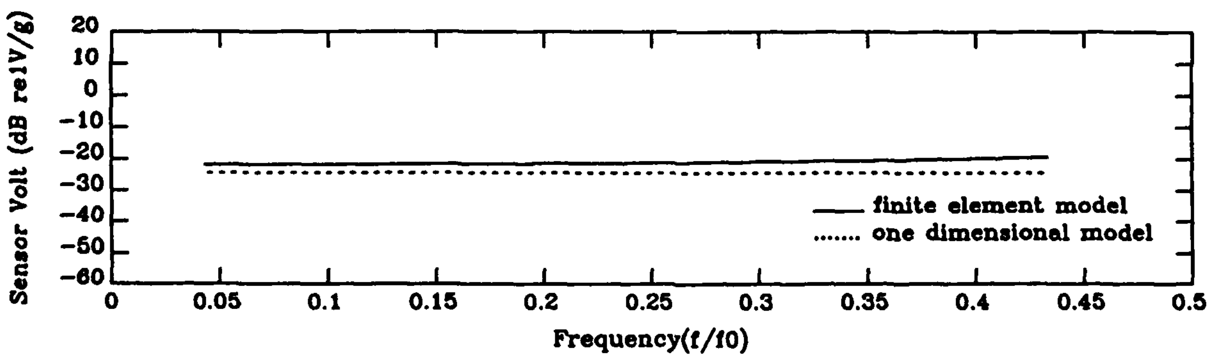
(Figure 6. continues)



6(b) Sensor Voltage



7(a) Surface Acceleration



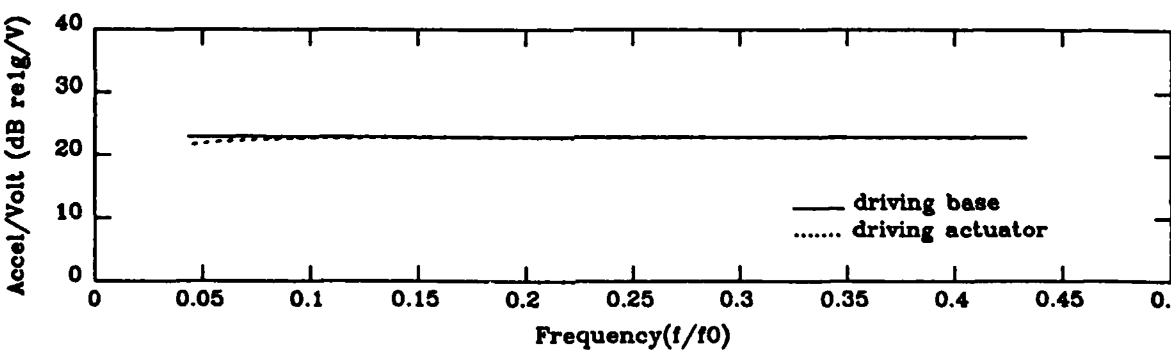
7(b) Sensor Voltage

Figure 7. MODEL RESULTS FOR BASE-DRIVEN CASE

Based on these results obtained from the baseline finite element model, several more computations were run with different material constants and/or boundary conditions. The two most interesting of these additional cases involve: 1) setting the d_{31} constant of the actuator material to zero and 2) specifying uniform displacements across the top surface of the actuator. In the first case, a voltage applied across the actuator drives only

thickness strains in that element and the extensional motion of the sensor depends only on Poisson's ratio of the material so that the actuator-driven condition is similar to the base-driven condition. The results obtained from this model indicate no drive dependence of the acceleration to sensor voltage ratio. The second variation of the finite element model involves the specification of an additional boundary condition while leaving the material constants unchanged. With this model in the actuator-driven condition, the d_{31} coupling causes extensional strains in the actuator; however, because the in-plane mechanical coupling is eliminated, these strains do not lead to similar displacements in the sensor element. Therefore the predicted transfer functions for this model are drive independent.

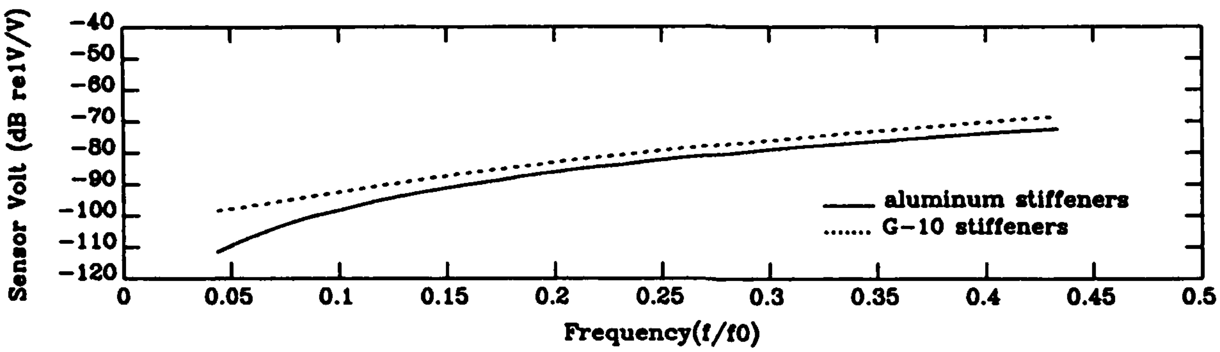
The results of these model variations indicate two potential solutions to the problem of the drive dependence of the transfer function. However, since it is not possible to change the properties of the material itself, only one practical solution remains, that is, to eliminate the in-plane mechanical coupling between the actuator and sensor. One way to do this is to use a stiffer material for the elastic interface layers of the isolator. Figure 8(a) shows the predicted transfer function for the case of aluminum stiffening layers in place of the G-10 stiffeners. The difference between the results for the two drive conditions is less than 2 dB at the lowest frequencies and decreases rapidly with frequency. The corresponding sensor voltages for the actuator-driven case and the base-driven case are presented in Figures 8(b) and (c), respectively. These results indicate that although the aluminum stiffeners greatly decrease the differences in the transfer functions, they do so at the expense of lower sensor voltages. The effective sensitivity of the sensor may be increased by using a heavier material such as steel rather than aluminum, if the system weight is not constrained. In fact, the model indicates that steel stiffeners not only increase the sensor voltage output, but completely eliminate the differences in the transfer functions for the two drive conditions.



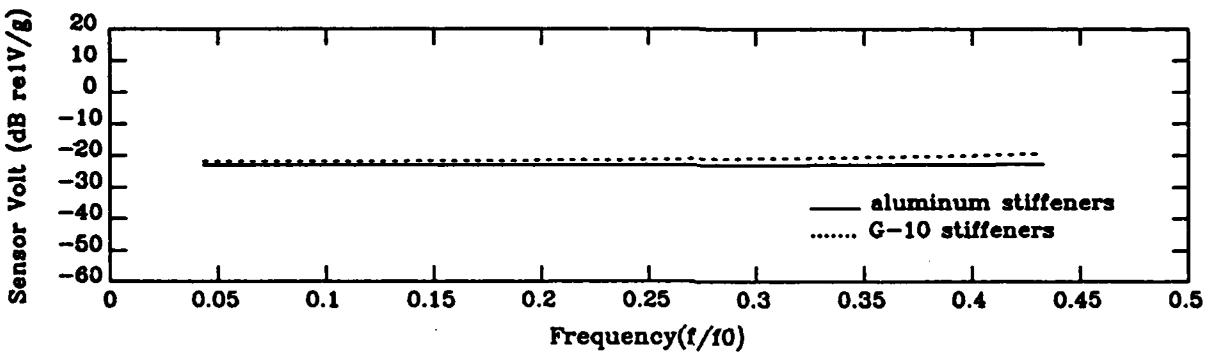
8(a) Ratio of Surface Acceleration to Sensor Voltage (continued)

Figure 8. COMPARISON OF G-10 AND ALUMINUM STIFFENING LAYERS

(Figure 8. continues)



8(b) Sensor Voltage for Actuator-driven Case



8(c) Sensor Voltage for Base-driven Case

SUMMARY

The work presented here demonstrates the importance of detailed modelling for a distributed isolation system using a piezoelectric composite material. A one-dimensional model fails to give an accurate prediction of the voltage output from the sensor element because of the absence of the d_{31} piezoelectric coupling and the Poisson effect in the model. The finite element model includes this coupling and gives good agreement with measured data. It has been shown that this thickness to extensional coupling is the cause of the dependence of the surface acceleration to sensor voltage ratio on the drive condition. A potential solution to this drive dependence lies in the use of stiffer, heavier elastic interface layers.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1991

3. REPORT TYPE AND DATES COVERED
Article from Proceedings

4. TITLE AND SUBTITLE Article Title:
Electromechanical Modelling of An Active Isolation System

5. FUNDING NUMBERS
P.E. #61153N
WU #59-0582-0-0
Assn #DNA580-030
Task #RR011-08-42

6. AUTHOR(S) M. D. McCollum, Code 5976
S. E. Forsythe, Code 5930
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Underwater Sound Reference Detachment
Naval Research Laboratory
P.O. Box 568337
Orlando, FL 32856-8337

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research via Naval Research Laboratory

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Proceedings Title: Conference on Recent Advances in Active Control of Sound and Vibration
15-17 April 1991 in Blacksburg, VA

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

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14. SUBJECT TERMS
Active Isolation
Sensors
Actuators
Piezocomposite Materials

15. NUMBER OF PAGES
19

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	SAR	SAR